Detailed numerical model for the resolution of molten salt storage tanks for CSP Plants

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Abstract

Considering the state-of-the-art in TES technologies, two-tank indirect system using molten salt is the most widespread within CSP plants. However, current techniques for design and optimization, as well as, for assessing the behaviour of these systems are mainly based on not-to-scale costly experimental set-ups. In this paper, a detailed numerical methodology modelling molten salt thermal storage tanks is presented. This methodology considers the transient behaviour of the molten-salt fluid, the gas ullage, the molten-salt free surface, the tank walls and insulation, different material in the foundation, radiation exchange between the salt and the tank walls in the ullage, the passive cooling in the foundation is proposed. Results for different configuration which allows an optimal design of the tank walls, insulation materials and tank foundations are presented.

1. Introduction

Concentrated solar power plants (CSP) are a well-proven technology for providing a significant share of renewable electricity in the near future. Combined with thermal storage, they can provide not only dispatchable electricity but also stability to the electricity network in case of high fraction of renewable production or intermittency due to cloudy weather conditions. Hence, thermal storage systems (TES) can be considered a key aspect for CSP plants due to their ability of extending solar power production beyond periods of no solar radiation reducing the mismatch between solar energy and demand.

Considering the state-of-the-art in TES technologies, two-tank indirect system using molten salt is the most widespread within CSP plants. Although the advantages of this technology against its competitors (PCM, solid, thermocline storages, etc.), there still are design aspects such as avoid the salt freezing by controlling the heat losses, optimization of the storage (aspect ratio, design of the inlet ports, etc.), which must be considered. However, current techniques for design and optimization, as well as, for assessing the behaviour of these systems are mainly based on not-to-scale costly experimental set-ups (see for instance [1, 2]). On the other hand, works conducting a numerical modelling of such systems are scarce in the literature. Can be cited the work carried out by J. Schulte-Fischedick et. al. [3]. They developed attempted the coupling of a CFD model using RANS for approaching the salt behaviour with a finite element method for the walls. The authors evaluated the cooldown of the molten salt. However due to the obvious demanding computational resources, different approximations were made.

In this sense, the present work aims at modelling the storage tank system of a CSP plant by proposing a detailed numerical methodology which considers the different parts of the storage as independent models, and solving the whole set of equations within a fully-coupled implicit finite volume methodology.

2. Detailed model for the molten salt-tank

In the present implementation the storage tank of a CSP plant is considered as the sum of different parts e.g. tank walls, tank foundation, molten-salt fluid, etc., such as shown in figure 1. The mathematical model considers the transient behaviour of the molten-salt fluid, the gas ullage, the molten-salt free surface, the tank walls and insulation, different materials in the foundation, radiation exchange between the salt and the tank walls in the ullage, the passive cooling of the foundation. In addition, for each element of the storage more than one model approach is considered. For example, for modelling the convection in the molten salt different levels of modelling might be considered depending on the desired accuracy [4]. The use of a modular simulation allows that for the same element 1D, 2D, 3D models can be used and at the same time, each element can receive a special treatment from the physical point of view (i.e. different hypothesis can be considered. Each of these elements (objects) are capable of solving themselves given determined boundary conditions, which can be obtained from the neighbouring elements (objects).

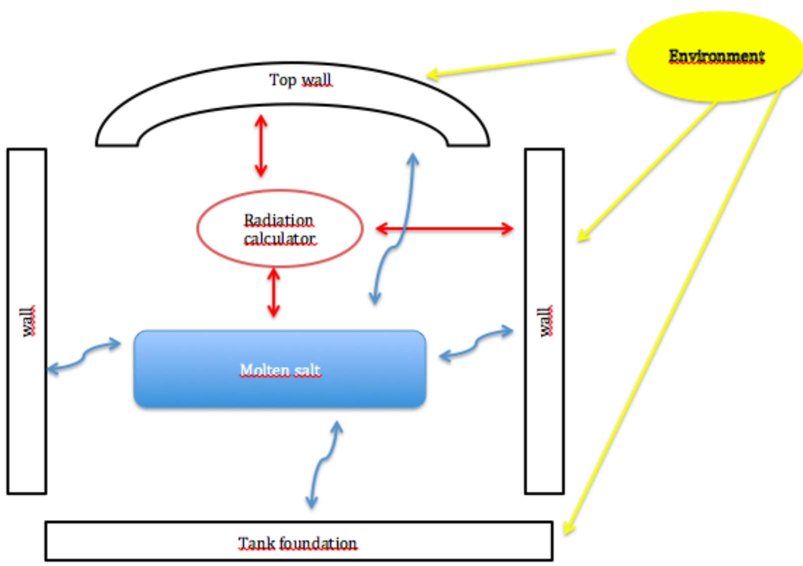

Figure 1: Schematic of the modular storage tank methodology

The implementation of the storage tank methodology has been made within the existing NEST platform [4] which allows the linking between different elements to perform a specific system or configuration.

The main advantages of a modular object-oriented tool are

i. any basic element programmed in a general way can be used in a given configuration and re-used in other systems;

ii. the elements which form a determined system interacts only through its boundary conditions, being solved independently which allows the change of a given model (e.g a 1D approach by a 3D approach) while the rest of the elements which form the system remains unchanged and,

iii. each element of a given system can be solved using a different parallelization paradigm without any need of re-writing any part of the code.

3. Mathematical model

A scheme of the energy balance at the different elements of the model and its boundary conditions is given in figure 2. The mathematical model considers the tank composed into these elements:

- Transient behaviour of the molten-salt
- The gas ullage
- The molten-salt free surface
- Tank walls and insulation
- Different material in the foundation
- Radiation exchange between the salt and the tank walls in the ullage.
- Passive cooling of the foundation

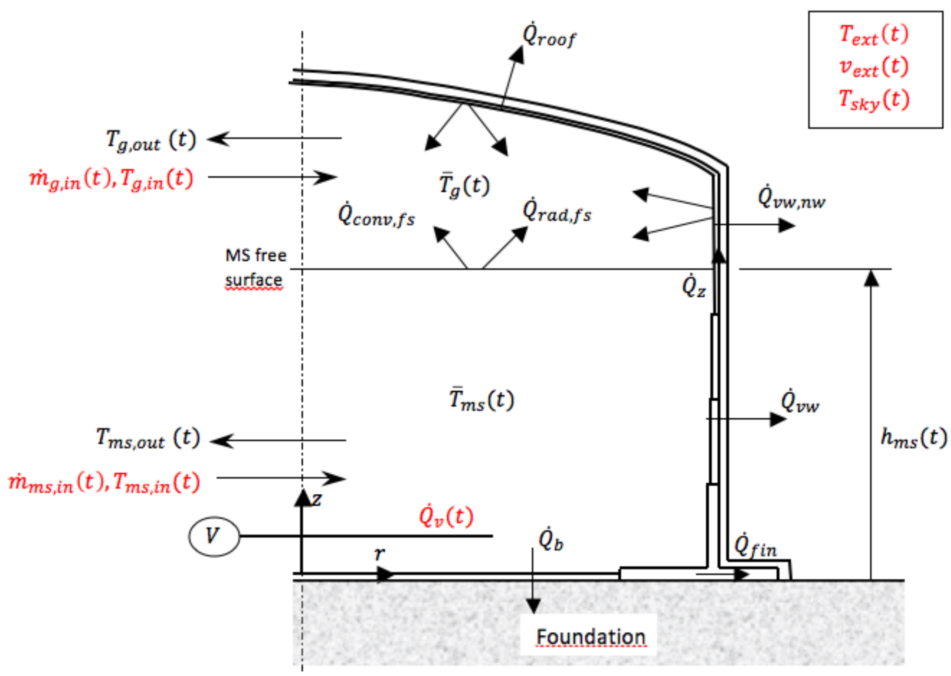

Figure 2: Boundary conditions of the different elements of the storage tank

The complete set of objects (elements) considered for the current implementation is given in Table 1. In addition, a brief mathematical description of some of these models is given hereafter.

Table 1. Elements considered in the storage tank model

Object/Model	**Description**
Molten-salt model	Global model for the energy balance of the molten-salt fluid
Gas ullage	Global model for the energy balance of the gas between the molten salt and the tank top walls (see fig. 2)
Molten-salt free surface	Global model for considering the free-surface of the molten salt
Wall	Single material layer with the one-dimensional heat conduction through a tank wall (i.e. container, insulation material, etc.)
Composite wall	Multiple material layer with three-dimensional heat conduction
Tank foundation	Solves the N material layer with one- dimensional heat conduction
Passive cooling	Global model for solving the energy balance of the passive cooling system implemented in the tank foundation
Radiation exchange	Object which calculates the radiation heat exchange between the different surfaces

3.1 Molten-salt global model

The molten-salt fluid can be evaluated by means of global balances as (see figure 2 for details)

$$\frac{d}{dt}\int_{V_{ms}} \rho_{ms} dV + \dot{m}_{ms}^{out} - \dot{m}_{ms}^{in} = 0 \tag{1}$$

$$\frac{d}{dt}\int_{V_{ms}} \rho_{ms} u_{ms} dV + (\dot{m}u)_{ms}^{out} - (\dot{m}u)_{ms}^{in} = -\dot{Q}_b - \dot{Q}_{vw} - \dot{Q}_{fs} + \int_{S_{ms}} \vec{v}_{ms} \cdot \vec{f}_{(\vec{n})} dS \tag{2}$$

where,

$\dot{Q}_b = \int_{S_b} \alpha_{ms}^{b} (\bar{T}_{ms} - T_t)\, dS$; is the heat losses through the tank foundations

$\dot{Q}_{vw} = \int_{S_{vw}} \alpha_{ms}^{vw} (\bar{T}_{ms} - T_t)\, dS$ is the heat losses through the vertical walls

$\dot{Q}_{fs} = \int_{S_{fs}} \left[\alpha_g^{fs}\left(T_{fs} - \bar{T}_g\right) + \varepsilon_{ms}\sigma T_{fs}^4 - \varepsilon_{ms}\dot{g}_{ms}\right] dS$ is the heat losses through the molten-salt free surface.

3.2 Tank walls and insulation

Any wall including the container and the insulation material, can be evaluated by means of a transient heat balance as,

$$\rho \quad c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \quad \nabla T \quad) \tag{3}$$

The above equation can be evaluated for each wall layer if the object is linked with the appropriate boundary conditions, for instance:

- With the molten-salt object as, $\alpha_{ms}^{vw}(\bar{T}_{ms} - T_t) = -\lambda_t \, \partial T_t / \partial r$
- With internal interfaces/walls as, $-\lambda_t \, \partial T_t / \partial n = -\lambda_i \, \partial T_i / \partial n$
- With external conditions as, $-\lambda_i \, \partial T_i \partial n = \alpha_{ext}(T_i - T_{ext}) + \varepsilon_i \sigma \left(T_i^4 - T_{sky}^4\right) - \dot{q}_s$

3.3 Foundation (N different materials)

Different layers can compose the foundation of the storage tank, each of these layers is evaluated as,

$$\rho_k c_{pk} \beta_k \frac{\partial T_k}{\partial t} = \nabla \cdot (\lambda_k \beta_k \nabla T_k) - \dot{q}_{v,k}, \quad k = 1,2, \dots, N \tag{4}$$

In general, $\beta_k = 1$ and $\dot{q}_{v,k} = 0$, except in the material with passive cooling. Depending on the layer, different boundary conditions are set

- Surfaces at the top, $-\lambda_k \frac{\partial T_k}{\partial z} = -\lambda_t \, \partial T_t / \partial z$
- Internal interfaces (surface k - surface l), $-\lambda_k \, \partial T_k / \partial n = -\lambda_l \, \partial T_l / \partial n$
- Lateral surfaces (far from the tank bottom), $\partial T_k / \partial n = 0$
- Bottom surface (far from the tank bottom), $T = T_{soil}$

4. Results

A preliminary illustrative transient thermal simulation of the molten-salt storage tank of Andasol plant has been here considered. The geometry data for this particular case have been taken from Monesa [5]) and J. Schulte-Fischedick et. al. [3]. In this case, cool-down processes of the hot (T_{hot}=384°C) and cold (T_{cold}=290°C) storage tanks are considered. In addition, as boundary conditions of the whole tank ambient temperature and soil temperatures are set as T_{ext}=25°C; T_{soil}=12°C, respectively.

Here, the working fluid is the solar salt (60% $NaNO_3$ – 40% KNO_3), the tank container is of steel A516gr70 and as insulation material for the lateral and roof walls Spintex342G-100 is used. Other details about geometry used are given hereafter:

- Storage tanks internal diameter and height $D = 38.5\ m$; $H = 14\ m$ (vertical walls).
- The vertical wall has different thicknesses as a function the tank height, $e = 0.039\ m$ $(0 \leq z \ll \Delta z)$; $e = 0.032\ m$ $(\Delta z \leq z \ll 2\Delta z)$; $e = 0.0255\ m$ $(2\Delta z \leq z \ll 3\Delta z)$; $e = 0.0185\ m$ $(3\Delta z \leq z \ll 4\Delta z)$; $e = 0.0115\ m$ $(4\Delta z \leq z \ll 5\Delta z)$; $e = 0.010 m$ $(5\Delta z \leq z \ll 6\Delta z)$, where $\Delta z = 2.333\ m$
- Similar to vertical wall, bottom wall also considers different thicknesses as a function of the distance from the tank center, $e = 0.008\ m$ $(0 \leq r \ll R_1)$; $e = 0.015\ m$ $(R_1 \leq r \ll R_3)$
- Insulation thickness: $e_i = 0.4\ m$ (hot tank); $e_i = 0.3\ m$ (cold tank).
- Foundation thicknesses: slip plate, $e = 0.006\ m$; dry sand, $e = 0.006\ m$; foam-glass, $e = 0.420\ m$; hard firebrick, $e = 0.060\ m$; insulating firebrick, $e = 0.360\ m$; heavy weight concrete, $e = 0.450\ m$; soil, $e = 9\ m$.

For the resolution of the cool-down process of both, hot and cold, molten-salt tanks the fluid has been solved using the global model coupled to the composite wall (multi-dimensional model). It has to be mentioned, that the mesh used for solving the solids walls and insulation materials is composed of about 1milion control volumes (CVs) and it has been required the use of parallelization techniques in order to speed-up the simulation of these elements. In addition, the free surface of the molten-salt fluid has been linked to the gas ullage object, which at the same time this element is linked to the roof of the tank (different layers of the wall object).

Illustrative results of the heat losses through the different walls for both, hot and cold, tanks are depicted in figure 4. These results are comparable to that obtained for J. Schulte-Fischedick et. al.[3] for a similar situation. However, although the results exhibit the same trend to that of the literature, there are differences in the global values obtained. For instance, total losses though the tank walls for the hot tank fully loaded yielded 194 KW against the 259 kW obtained by J. Schulte-Fischedick et. al. [3]. Main differences are obtained in the top walls, but might be due not only to the differences in the models used, but also in the geometry of the tank. Here we are considering all details of the real geometry as variable wall thicknesses (in both lateral and bottom wall). Other issue to take into account is the definition of the boundary conditions for the case, which is not exactly the same as those considered in the literature (they are not fully specified in the referred article).

In spite of the differences with previous results, it is shown how the current methodology is capable of predicting the evolution of the heat losses as the tank is charged (or discharged). For instance, for the given conditions, when the hot tank is fully loaded energy losses through the lateral walls represents almost 41 % of the total energy lost, whereas the losses through the free-surface are the 45%. As the tank is emptied, these ratios are changed. In fact, when the tank is empty, most of the losses are accounted through the free surface of the tank being 75.5 % of the total losses. Similar trends are observed for the cold tank, but ratios vary slightly respect to the hot tank.

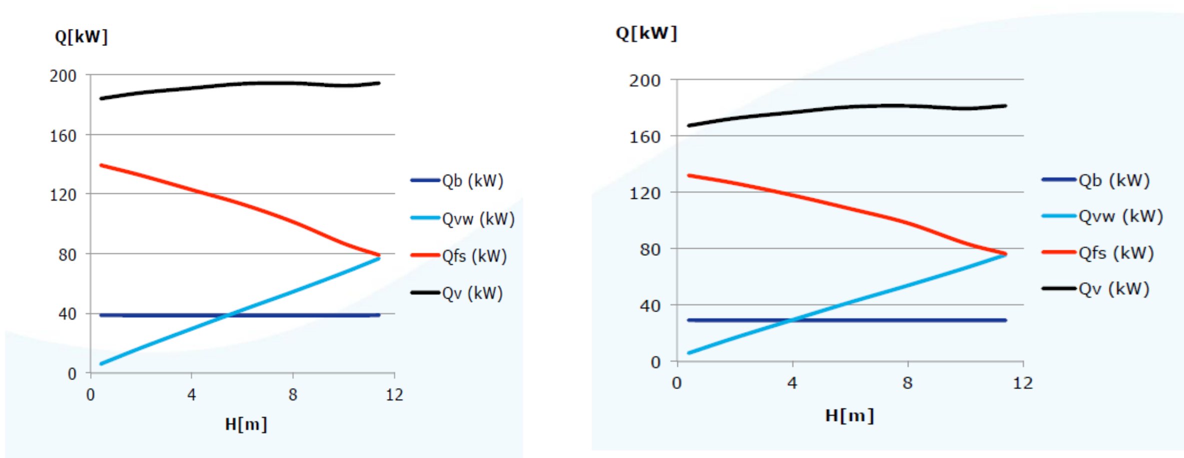

Figure 4. Heat losses as a function of the molten-salt height

Another important feature of the present methodology is that it is possible to carry out the parametrization of the different elements of the tank in order to find the best tank configuration for a given situation. Figure 5 depicts the influence of the heat losses through the different walls as a function of the vertical wall thickness for the hot tank.

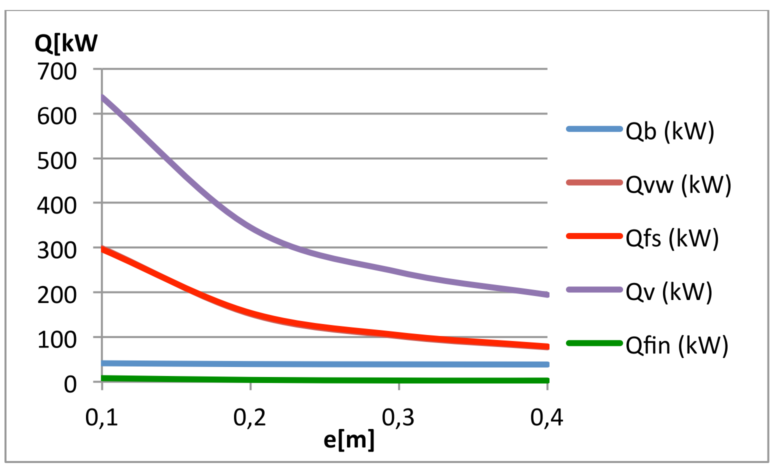

Figure 5. Heat losses through the different walls as a function of the tank thickness for the hot tank.

5. Concluding remarks and future work

A modular object-oriented methodology has been used for the transient thermal and fluid dynamic simulation of molten-salt storage tanks for CSP plants. This methodology takes advantage of the existing NEST platform [4] to develop a versatile methodology which implements different levels of modelling for the components of a storage tank. These elements interact between each other by means of the boundary conditions, while the global algorithm implemented in NEST platform allows their coupled resolution at each time step. One of the advantages of this kind of modelling is that each element is programmed (and validated) once but can be used several times and in different ways (e.g.

wall model can be set-up as an insulation vertical wall or as part of the foundation). Thus, different configurations can be made by just changing the way each object is linked.

References

[1] M. S. Sohal, P. Sabharwall, P. Calderoni, A. K. Wertsching, B. S. Grover and P. Sharpe. Conceptual design of forcer convection molten salt heat transfer testing loop. Technical report INL/EXT-10-19908. Idaho National Laboratory. 2010

[2] M. M. Rodríguez-García, E, Zarza Moya, J. León Alonso, J. Fernández RecheDesign and construction of an experimental molten salt test loop. SolarPaces Granada, 2011.

[3] Schulte-Fischedick, J. et. al. 2008 CFD analysis of the cool-down behaviour of molten salt thermal storage systems. Energy Sustainability

[4] Damle, R., Lehmkuhl, O., Colomer, G., Rodriguez, I., 2011. *Energy Simulation of Buildings with a Object-Oriented Tool*. In Proceedings of the ISES Solar World Congress, Kassel, Germany

[5] Monesa I. & C. 2007. *Ficha Técnica*

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Nomenclature

C_p	Specific heat capacity	J/kgK	t	Time	s
$\dot{m}$	Mass flow rate	kg/s	u	Velocity	m/s
$\dot{Q}$	Heat losses	W	V	Volume	m^3
S	Surface area	m^2	z	Axial direction	m

Greeks

α	Superficial heat transfer coefficient	W/m^2K	σ	Stefan-Boltzmann constant	
ε	Emissivity		ρ	density	kg/m^3
λ	Thermal conductivity	W/mK	Δ	coordinate increment	

Subscripts

b	bottom surface	ms	molten salt
ext	ambient conditions	out	outlet conditions
f.s.	free surface	t	tank container
i	insulation	vw	vertical wall
in	inlet conditions		